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Effects of a Freely Moving Maintenance Device on the Hydrodynamic Characteristics of Pipe Bends

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ABSTRACT

Regular inspection and maintenance of oil and gas pipelines is crucial for safe and cost effective operation of oil and gas industry. Various techniques are practised globally for this purpose. One such technique is to insert a maintenance device within the pipeline that can monitor and record various parameters of interest, such corrosion etc., for in-situ inspection and repair of the pipeline. The shape of maintenance device is conventionally rectangular and it houses different sensors to monitor pipeline condition. The maintenance device are thus hollow and can propagate freely within the pipeline. Extensive research has been carried out on the use and effects of such maintenance devices in straight pipes, however, published literature regarding their use in pipe bends is severely limited. In the present study, an advanced numerical approach has been used to investigate the effects of the presence of a maintenance device on the flow structure and hydrodynamic characteristics of hydraulic pipe bends used within oil and gas sector. A novel methodology has been used, and verified, to predict the velocity of the maintenance device within pipe bends. It has been observed that after the maintenance device is inserted in a pipe bend, the flow structure within the bend changes significantly. The flow within the bend has been noticed to become highly non-uniform, with the generation of considerable amount of secondary flows. This leads to substantial increase in the pressure drop across the bends. This information can be integrated in the pipeline design for better accuracy.

Keywords

Computational Fluid Dynamics (CFD), Pipe Bends, Maintenance Device, Q-criteria, Pressure Drop.

1. INTRODUCTION

Bends are an integral part of any pipeline network. Due to severe flow velocity gradients present within pipe bends, their maintenance often becomes more important than straight pipes. A conventional maintenance device is essentially a hollow rectangular body in which the sensors are installed for in-situ condition monitoring. Vlasak and Myska [1]-[2] were probably amongst the initial researchers who experimentally investigated the effects of maintenance devices on the hydrodynamic characteristics of hydraulic pipe bends. They analysed the maintenance devices in pipe bends of various radii of curvature (R/r=2 and 5). They reported that as the average flow velocity (Vav) increases, the velocity of the maintenance device (Vc) also increases, however, this increase in maintenance device's velocity is non-linear. At lower flow velocities, this increase is quite substantial while at higher flow velocities, this increase becomes more gradual. The ratio of maintenance device-to-flow velocities (Vc/Vav) is termed as Holdup velocity (H). It has been reported that H can attain a maximum value of 120% of Vav. As the study was purely experimental, the authors were unable to record and analyse the flow structure within the pipe bends.

Asim et al [3]-[7] have extensively reported the effects of the presence of maintenance devices in hydraulic pipelines. The maintenance devices investigated were of various shapes; spherical, cylindrical, rectangular etc. As these studies were mostly numerical, the flow structure within pipe bends has been reported to some extent, mostly qualitative. The authors have shown that the shape factor of the maintenance device is an important factor as far as the hydrodynamic characterisation of the pipe bends is concerned. These studies however lack detailed flow diagnostics within the bends, for example, it has been reported in various studies [8]-[9] that the presence of maintenance devices offer more resistance to the flow, and thus, secondary flows become dominant in pipe bends. Analyses regarding the formation and strength of the secondary flows within hydraulic pipe bends have not been reported by Asim et al [3]-[7].

More recently, Abushaala [10] has reported that the flow structure become highly non-uniform once a maintenance device in injected within a pipe bend. First order velocity based analyses have been presented by the author indicating that the flow velocity becomes considerably higher in the gap regions between the maintenance device and the bend wall. This is particularly interesting as H has been recorded to be more than 1. This aspect of the study needs detailed investigation in order to ascertain the role of secondary flows in the hydrodynamic characterisation of pipe bends. Hence, in the present study, a numerical approach, similar to Abushaala [10] has been adopted to analyse the effects of a conventional (rectangular) maintenance device on the flow structure within hydraulic pipe bends. An important point to note here is that Abushaala [10] used a simplistic approach to calculate the velocity of the maintenance device, while in the present study, a novel technique has been used, and verified, for this purpose.

2. NUMERICAL METHODOLOGY

A commercial Computational Fluid Dynamics (CFD) based solver, Ansys 18.1, has been used to carry out the numerical work presented in this study. The geometry of the pipe bend has three separate sections i.e. inlet pipe, test section and outlet pipe. This has been purposefully done because it takes about 50D length of the pipe for the flow to become fully developed, D being the diameter of the pipeline. Thus, 50D long inlet and 10D long outlet sections have been numerically modelled, while the test section has an equivalent length of 1m, as shown in figure 1. Two different 90° pipe bends, having R/r of 4 and 8, have been used in the present study. The maintenance device has been injected within the pipe bend at 45°. It has been shown by Asim [3] that the average velocity of the maintenance device within a hydraulic bend of 90° is most closely related to its velocity at 45°. The hydraulic diameter of the maintenance device considered is 40% of the pipeline diameter.

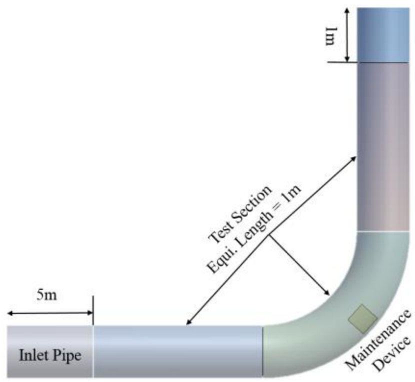


Figure 1. Geometric model of R/r=4 pipe bend with the maintenance device.

The concept of hybrid meshing has been incorporated for meshing the flow domain. A structured hexahedral mesh is generated in the inlet and outlet sections, while an unstructured tetrahedral mesh has been generated within the test section, due to the geometrical complexities arising from the presence of the maintenance device. The mesh density within the test section is significantly higher than in the inlet and outlet section for better accuracy of numerically predicted flow structures. Mesh element size in the test section is thus 4mm, while in the inlet and outlet sections is 8mm. The resulting mesh contains 1.2million mesh elements, as shown in figure 2.

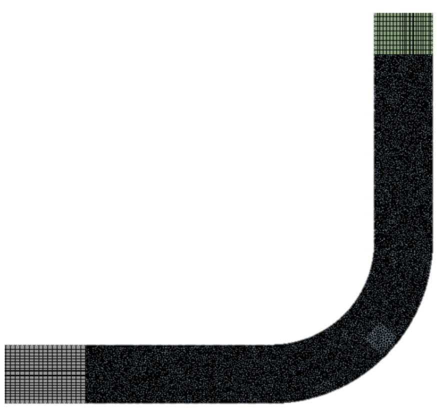


Figure 2. Meshing of the flow domain.

In order to achieve accurate results which are independent of the mesh sizing used, another mesh with 2.4million mesh elements has been generated. The numerically predicted results, after running simulations using both the meshes for the case where Vav=1m/s and R/r=4, depict that the difference in the pressure drop across the pipe bends is less than 1% between the two meshes. Hence, mesh with a size of 1.2million elements has been chosen for further numerical investigations.

The prediction of maintenance device's velocity within pipe bends is quite complicated as the trajectory of the maintenance devices keeps on changing while passing through the bend. A novel technique, called Discrete Phase Modelling (DPM), has been used in the present study to numerically predict the orientation and Vc at 45°. DPM computes the trajectories and velocities of discrete phase entities i.e. maintenance devices. Calculation of maintenance device's velocity, using a Lagrangian formulation, includes the device's inertia, hydrodynamic drag and the force of gravity. DPM also predicts the effects of turbulence on the maintenance device due to turbulent eddies present in the continuous phase i.e. water. Hence, the orientation and the velocity of the maintenance device have been computed using DPM. The numerically predicted velocity of the maintenance device has been verified against the experimental measurements published by Agarwal et al [11], as shown in figure 3. It can be seen that DPM predicted Vc is in close agreement with experimentally measured Vc.

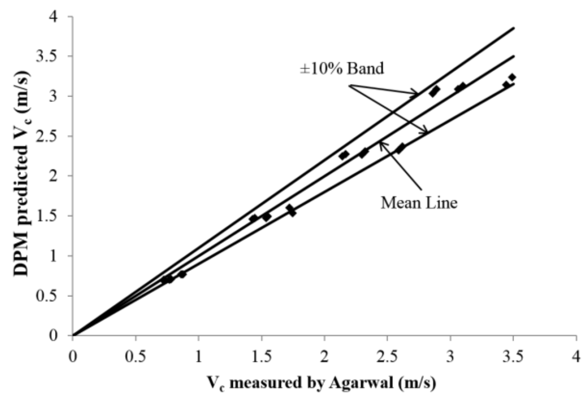


Figure 3. Variations in Vc numerically and experimentally recorded.

Three dimensional time-averaged Navier-Stokes equations, along-with the continuity equation, have been iteratively solved for steady-state turbulent flow of water, and maintenance device, within pipe bends. Flow turbulence has been modelled using 2-equation SST k-ω model due to its proven superiority in accurately modelling the wake regions and extreme pressure gradients, which are expected to occur in the present case. The density and dynamic viscosity of water specified are 998.2kg/m^3 and 0.001003kg/m-s (at NTP condition). SIMPLE pressure-velocity coupling algorithm has been employed along with 2nd order Upwind gradient and interpolation schemes for better accuracy of numerically predicted results.

3. RESULTS AND DISCUSSIONS

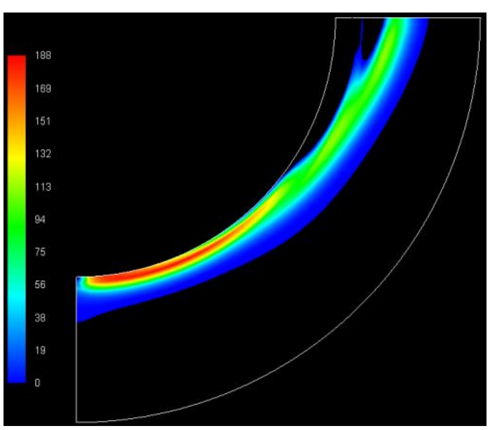
Before moving on to the flow diagnostics within hydraulic bends having rectangular shaped maintenance devices present within, water flow behaviour alone needs to be investigated. As the focus of the present study is on the formation and strength of secondary flows within pipe bends due to maintenance device, a method which is based on the velocity gradient tensor has been adopted. A unique parameter, called Q-criteria, has thus been used to analyse the flow structures within pipe bends, where Q-criteria is defined as:

$$Q = 1/2\ (\omega^2 - SR^2) \tag{1}$$

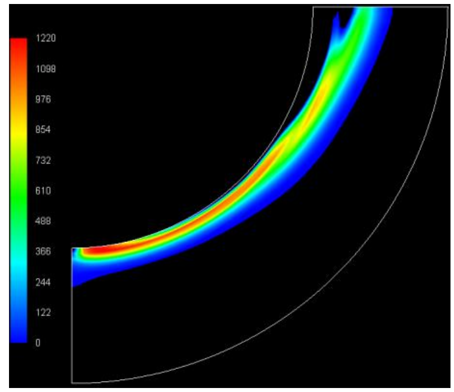
where ω is the vorticity magnitude (/s), while SR is the strain rate (/s). The Q-criterion defines secondary flows (a vortical structure) as a connected fluid region with a positive second invariant of the velocity gradient tensor i.e. $Q>0/s^2$. This criterion also adds a secondary condition on the pressure, requiring it to be lower than the surrounding pressure in the vortical structure [12].

Variations in positive Q-criteria within a hydraulic pipe bend of R/r=4 at Vav=1m/s are shown in figure 4(a). It can be observed that the vortical structures are predominantly formed along the inner wall of the bend where Q-criteria can be as high as 188/s. These structures have been noticed to occupy most of the inner regions of the bend where the flow velocity is low and the chances of flow detachment is high. Thus, the vortical structures can be seen to detach from the bend's inner wall downstream the bend (around 45°). The Q-criteria value keeps on decreasing downstream the bend. The vortical structures can be clearly seen to penetrate the flow domain after the bend as well. The pressure drop across the bend has been recorded to be 150Pa,g, which is about 58Pa,g higher than in a straight pipe of same length. Hence, the hydrodynamics of a bend are significantly different than a straight pipe due to the presence of secondary flows within them.

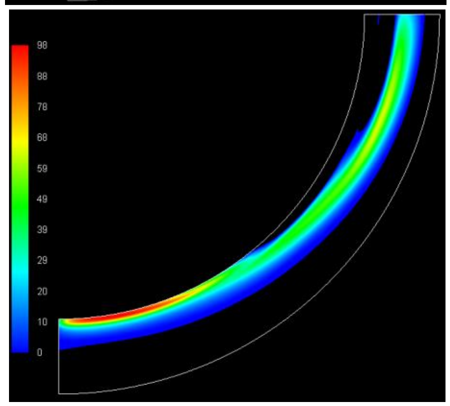
In comparison with figure 4(a), it can be seen in figure 4(b) that the maximum positive value of Q-criteria increases 5.5 times as the average flow velocity increases to 4m/s i.e. 4 times. Qualitatively, the distribution of vortical structures within the bend remains nearly the same, apart from the fact that the flow detachment occurs much sooner (around 30°) due to the severe velocity gradients that exist within pipe bends, and increases as the flow velocity increases. Thus, the inward curling of the streamlines occur sooner than at lower flow velocities. The total pressure drop in this case has been recorded to be 1644Pa,g, which is 11 times higher than at Vav=1m/s. In a straight pipe, the pressure drop would be 1472Pa,g at the same average flow velocity, which means that the additional pressure drop due to bend's curvature is 172Pa,g. This additional pressure drop is 2.96 times higher than at Vav=1m/s. Furthermore, the variations in positive Q-criteria within a bend of R/r=8 is shown in figure 4(c). It can be clearly seen that the maximum value of Q-criteria is 48% less than for R/r=4. This is due to the straightening of the bend where the equivalent length remains the same. The pressure drop, as expected, is 117Pa,g which is 11% lower than for R/r=4, indicating that R/r=8 bends offer lesser resistance to the flow as compared to R/r=4 bends.



(a)



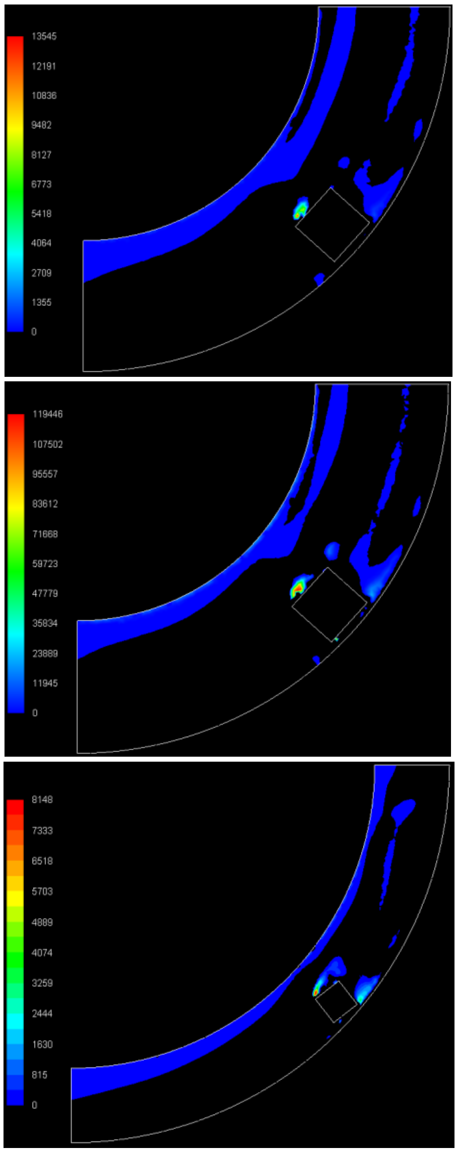
(b)



(c)

Figure 4. Variations in positive Q-criteria within hydraulic pipe bends (a) R/r=4 at Vav=1m/s (b) R/r=4 at Vav=4m/s (c) R/r=8 at Vav=1m/s.

The effects of the presence of a rectangular shaped maintenance device within hydraulic pipe bends have been analysed here for the same conditions discussed above. It can be seen in figure 5(a) that a maintenance device alters the distribution of vortical structures within pipe bends considerably. The maximum value of positive Q-criteria increases as much as 13545/s, which is 71 times higher than the case when the maintenance device was not present within the bend. Very high values of Q-criteria have been observed on the top front surface of the device where the flow detaches itself from device's surface. Further vortical structures are formed downstream the device, emerging from the bottom rear surface of the device. These additional high-strength vortical structures adds to flow resistance, increasing the pressure drop across the bend to 305Pa,g, which is twice as high as compared to the flow of water only in the same bend at the same average flow velocity. Figure 5(b) depicts that as the flow velocity increases to 4m/s, although the distribution of vortical structures within the pipe bend remains the same, their strength increases substantially. The maximum value of positive Q-criteria has been recorded to be 119446/s, which is 7.8 times higher than at Vav=1m/s. This increase was recorded to be 5.5 times for water flow alone, hence, the rest of 2.3 times increase is due to the maintenance device alone. The pressure drop in this case is 4510Pa,g, which is 13.7 times higher compared to the previous case i.e. Vav=1m/s. As R/r increases to 8 in figure 5(c), the maximum positive Q-criteria and the pressure drop across the pipe bend decrease to 8148/s (39%) and 270Pa,g (11.5%) respectively. These observations are in-line with the previous observations for water flow only i.e. as R/r of the bend increases, both the pressure drop across it and the strength of the vortical structures present in it decrease. An interesting observation to note here is that the presence of the maintenance device within pipe bends delay the detachment of flow from the inner walls of the bends.



(a) (b) (c)

Figure 5. Variations in positive Q-criteria within hydraulic pipe bends having the maintenance device (a) R/r=4 at Vav=1m/s (b) R/r=4 at Vav=4m/s (c) R/r=8 at Vav=1m/s.

4. CONCLUSIONS

From the numerical results presented in this study regarding the presence of a maintenance device within hydraulic pipe bends, it can be concluded that maintenance device significantly alters the flow structure within bends by offering more resistance to the flow, even when the hold-up velocity is more than 1. Maintenance devices increase the maximum positive Q-criteria values and the pressure drop across the bends, due to the formation of high-strength vortical structures at the top front and bottom rear surfaces of the devices. Increase in average flow velocity results in the increase in pressure drop and Q-criteria values, while increase in R/r of the bend decreases these parameters, due to reduction in bend's curvature. These results can be used in the design phase of such pipelines to accommodate the cost of carrying out pipeline inspection and maintenance.

5. REFERENCES

[1] Vlasak, P., Myska, J. (1983). "The Effect of Pipe Curvature on the Flow of Carrier Liquid Capsule Train System", *In Proceedings of the Institute of Hydrodynamics*, Praha, Czech Republic.

[2] Vlasak, P., Berman, J. (2001). "A Contribution to Hydro-transport of Capsules in Bend and Inclined Pipeline Sections", *Handbook of Conveying and Handling of Particulate Solids*, pp. 521-529.

[3] Asim, T. (2013). *"Computational Fluid Dynamics based Diagnostics and Optimal Design of Hydraulic Capsule Pipelines"*, PhD thesis, University of Huddersfield, UK.

[4] Asim, T. Mishra, R. (2016). "Computational Fluid Dynamics based Optimal Design of Hydraulic Capsule Pipelines Transporting Cylindrical Capsules", *International Journal of Powder Technology*, 295, pp. 180-201.

[5] Asim, T. Mishra, R. Abushaala, S. Jain, A. (2016). "Development of a Design Methodology for Hydraulic Pipelines carrying Rectangular Capsules", *International Journal of Pressure Vessels and Piping*, 146, pp. 111-128.

[6] Asim, T. Mishra, R. (2018). "Effect of capsule shape on hydrodynamic characteristics and optimal design of hydraulic capsule pipelines", *Journal of Petroleum Science and Engineering*, 161, pp. 390-408.

[7] Asim, T. Mishra, R. (2016). "Optimal Design of Hydraulic Capsule Pipelines Transporting Spherical Capsules", *The Canadian Journal of Chemical Engineering*, 94, pp. 966-979.

[8] Ellis, H. S. (1974). "Minimising the Pressure Gradients in Capsule Pipelines", *The Canadian Journal of Chemical Engineering*, 52, pp. 457-462.

[9] Kruyer, J. Redberger, P. J. Ellis, H. S. (1967). "The Pipeline Flow of Capsules: Part 9", *Journal of Fluid Mechanics*, 30, pp. 513-531.

[10] Abushaala, S. (2013). *"Hydrodynamic Analysis and Optimal Sizing of Pipelines Transporting Spherical Capsules"*, PhD thesis, University of Huddersfield, UK

[11] Agarwal, V. C. Singh, M. K. Mathur, R. (2001). "Empirical Relation for the Effect of the Shape of the Capsules and the End Shape on the Velocity Ratio of Heavy Density Capsules in a Hydraulic Pipeline", *In Proceedings of the Institute of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*.

[12] Kolar, V. (2007). "Vortex Identification: New Requirements and Limitations", *International Journal of Heat and Fluid Flow*, 28, pp. 638-652.